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Nursery Practices That Improve Hardwood Seedling Root Morphology

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*Three years of work at the State forest nurseries in Illinois, Indiana, Iowa, Missouri, and Ohio have shown that bed density control, undercutting, and seed source control can influence the root system morphology of northern red oak (*Quercus rubra *L.), white oak (*Q. alba *L.), and black walnut (*Juglans nigra *L.) seedlings. Red and white oak seedlings with five or more permanent first-order laterals (roots > 1 mm in diameter) and walnut seedlings with eight or more such laterals survive longer and compete better after field planting than seedlings with fewer lateral roots. Undercutting red oak after the second or third flush of stem growth is complete and undercutting walnut during mid- to late July results in more laterals because wound roots develop near the cut surface. Seed source also had an effect on the number of laterals produced by seedlings.* Tree Planters' Notes 41(3):21–32; 1990.

Managers of bareroot nurseries work hard to produce the highest quality seedlings possible. They face a challenging job. No two nurseries are alike, and variations of soils and microclimates within a nursery may be as great as variations between nurseries. Variability of climate and seed crops produces situations that are not easily controlled by the nursery manager and may dramatically affect the quality of the crops.

Variability can be reduced in part by cultural practices. Forest nurseries in five of the Central States (Iowa, Illinois, Indiana, Missouri, and Ohio) have established a cooperative to improve cultural control of hardwood seedling quality. This paper will summarize 3 years of work by the cooperative and suggest standards for improving root and shoot characteristics of northern red oak (*Quercus rubra* L.), white oak (*Quercus alba* L.), and black walnut (*Juglans nigra* L.) through bed density control, undercutting, and seed-source control. Red oak and black walnut will be discussed in detail.

The commercial production of bareroot seedlings subjects them to stress not encountered by similar plants in a natural setting. Roots that are cut and extracted from their normal environment are exposed to the harshest of conditions. As a result, lateral roots less than 1 mm in diameter are usually lost. This loss produces an imbalance in the shoot to root ratio and reduces the chance for successful field establishment and competitive growth of seedlings. If sufficient large first-order lateral roots are not present, the seedlings will either not survive or not grow competitively when field planted.

First-order lateral roots greater than 1 mm in diameter (permanent laterals) are needed to provide sites for regenerating higher order roots. In recent studies *(1-8)*, researchers have suggested that there is a critical number of permanent first-order laterals needed to ensure that each species survives and grows when planted in the field. Most of the work of the cooperative has focused on increasing the number of permanent roots of oak and walnut seedlings and on field testing the responses.

Bed density and undercutting were identified as two cultural treatments that could directly increase the number of permanent roots. Both shoots and roots of seedlings respond to the space in which they grow. As bed density increases, roots seem to be more restricted than shoots. Healthy shoots can be produced from deficient root systems in the nursery because ideal conditions of moisture and nutrition are easily supplied. However, seedlings with good shoots but deficient roots respond poorly in the field.

Undercutting is the practice of drawing a blade horizontally through the soil at a given depth below the root collar, at a time

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other than lifting. The term *root pruning*, which has also been used to identify this practice, is better defined as the practice of clipping off excess lengths of roots after the seedling has been lifted from the nursery bed.

The rationale for undercutting can be found in nature. Naturally growing root systems are constantly being injured as they hit rocks in the soil or are damaged and consumed by soil organisms. Replacement roots are rapidly produced because the wounded area acts as a carbon sink, attracting sugars from elsewhere in the plant. As a result, three to six *wound roots* develop rapidly at or just above the wound. These same roots are produced from the lifting wound after the seedling is field planted, and act as permanent roots produced from the taproot.

Undercutting also makes sense in the nursery setting because seedlings such as oak and walnut can produce radicles growing 18 to 24 inches deep during the first growing season. These seedlings are normally lifted at 10 to 12 inches, thus cutting off a significant portion of the radicle. If these radicles were cut at a depth of 6 to 8 inches and new wound roots were produced, the lifted seedlings would have more potential sites for higher order root regeneration. Such seedlings would be more competitive in the field.

Methods

In the spring of 1987, the present state of seedling production was characterized in a preliminary study. Five-hundred randomly selected, ungraded seedlings of northern red and white oak and black walnut were examined from all but two of the cooperating nurseries (the Jasper-Pulaski and Vallonia Nurseries in Indiana). Routine cultural practices for each nursery were used to raise these 1 + 0 bed-run seedlings. Bed densities varied among the nurseries and ranged from 8 to over 20 per square foot. Samples were collected by selecting 10 to 15 seedlings from 10 randomly located positions in 400-foot-long beds. Seedlings were kept fresh, then bagged and shipped to Ames, IA, for analysis. Seedling measurements included

- height from the root collar to the base of the terminal bud.
- diameter measured at approximately 0.5 inch above the root collar.
- the number of first-order roots greater than 1 mm.

During spring 1987, studies were established to test the effect of bed density and undercutting on the production of first-order roots at each nursery (except for the Vallonia Nursery). Densities of 3, 6, and 12 seedlings per square foot for northern red and white oak and of 3, 6, and 9 per square foot for black walnut were used. These densities were established by thinning existing seedlings from the beds. Half the plots were undercut when taproots at their 6-inch depth measured 1/4 to 1/2 inch in diameter. Plots received the fertilizer, weeding, and irrigation treatments customary at their respective nurseries.

Seedlings at each nursery were lifted during spring 1988; 40 were randomly selected from each subplot (160 to 240 seedlings per treatment). The same criteria were used to measure the seedlings. In addition to the number of permanent first-order lateral roots, the number of wound roots was also counted. Wound roots were identified as roots arising at or just above the wound created by the undercutting blade.

During the 1988 growing season, various combinations of frequency and timing for undercutting were applied at different nurseries. Frequency of undercutting ranged from zero to seven. Timing ranged from as early as the second week in June to as late as the last week in August.

In addition to studies of the timing and frequency of undercutting, progeny comparisons for up to ten mother trees for each species were established at each nursery. Seedlings were grown at a density of 6 per square foot and were not undercut.

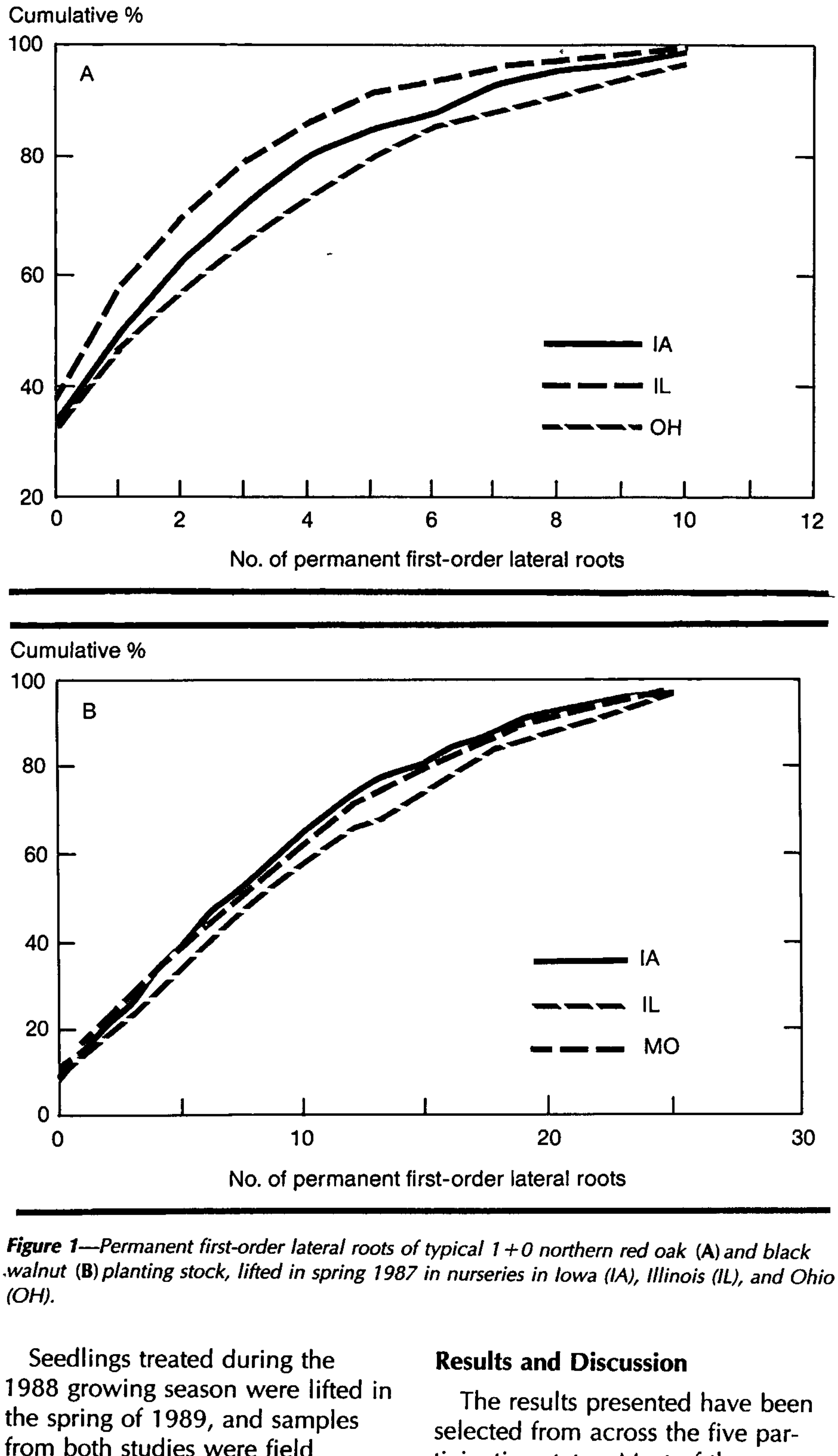

***Figure 1**—Permanent first-order lateral roots of typical 1+0 northern red oak* (**A**) *and black walnut* (**B**) *planting stock, lifted in spring 1987 in nurseries in Iowa (IA), Illinois (IL), and Ohio (OH).*

Seedlings treated during the 1988 growing season were lifted in the spring of 1989, and samples from both studies were field planted at their respective local nurseries or at a site near Newton, IA.

Results and Discussion

The results presented have been selected from across the five participating states. Most of these preliminary responses are duplicated in the other states. Those selected for inclusion show some of the clearest trends.

Bed-run responses. Permanent first-order lateral roots were counted on bed-run seedlings sampled during the spring of 1987 (fig. 1A and 1B). These seedlings were grown at accepted nursery bed densities and thus provide a picture of typical planting stock before the implementation of density and undercutting studies. Depending on the nursery, we found that 56 to 70% of the red oak seedlings had less than two permanent first-order lateral roots and that only 8 to 20% of the red oak seedlings had five or more permanent first-order lateral roots (fig. 1A). Data for white oak seedlings at the Missouri and Ohio nurseries (not included in the graphs) indicated that 32 to 34% of the seedlings, depending on the nursery, had fewer than three permanent first-order laterals and that 37 to 42% had five or more.

We also found that 12 to 16% of the walnut seedlings, depending on the nursery, had less than two permanent first-order lateral roots and that 67 to 72% had five or more (fig. 1B). Forty-eight to 56% of walnut seedlings had eight or more permanent, first-order laterals.

The range in percentages shows the variations among nurseries before the use of undercutting or specific density controls. Because of inherent nursery differences such as site, climate, seed source, and cultural practices, one would not expect to have the same percentages. However, the distribution

Table 1—*Responses of red oak seedlings to bed density and undercutting*

Density/ undercutting	Height (in)	Diameter (in)	No. of permanent roots > 1 mm		
			1st-order	Wound	Total
Illinois					
3/ft²					
Yes	15.3	0.32	13.4	6.1	19.5
No	20.9	0.39	10.8	—	10.8
6/ft²					
Yes	14.9	0.29	10.6	5.8	16.4
No	19.1	0.33	8.8	—	8.8
12/ft²					
Yes	15.2	0.27	8.7	6.2	14.9
No	18.1	0.30	6.6	—	6.6
	D,U,DU	D,U,DU	D,U		
Indiana					
3/ft²					
Yes	16.2	0.27	11.8	4.0	
No	18.8	0.31	14.8	—	
6/ft²					
Yes	16.1	0.25	11.5	4.8	
No	17.3	0.26	12.4	—	
12/ft²					
Yes	15.3	0.24	8.0	4.9	
No	17.2	0.25	9.5	—	
	D,U	D,U,DU	D,U	D	
Ohio					
3/ft²					
Yes	16.2	0.30	14.3	2.2	
No	17.8	0.30	12.0	—	
6/ft²					
Yes	15.5	0.26	9.8	1.8	
No	15.9	0.27	8.4	—	
12/ft²					
Yes	13.2	0.23	7.2	1.3	
No	15.0	0.25	7.1	—	
	D,U	D,U	D,U,DU	D	

Wound roots are roots > 1 mm developing around the undercutting wound. Significant (α = 0.01) effects of density (D), undercutting (U), and density by undercutting interaction (DU) were noted for the indicated characteristics.

of the number of roots among nurseries is fairly consistent, especially for walnut.

Preliminary data suggest that five or more permanent first-order laterals are needed for red and white oak, and eight or more for walnut seedlings to establish successfully in the field (unpublished data). The large number of seedlings having insufficient numbers of these critical roots suggests that introducing a large cull factor, based on root system quality, into grading systems would assure high-quality planting stock. On many seedlings, however, cultural practices could be modified to reduce the cull percentage by increasing the number of permanent first-order laterals.

Response to density and undercutting. In spring 1987, we began a study to determine the effects of density and undercutting on the number of first-order lateral roots, and the initial height and diameter of seedlings (tables 1 and 2). For red oak and walnut, there was a decrease in height growth as bed density increased and as undercutting was done. These results are expected: increased root density increases competition for space, whereas undercutting changes the source-sink response for carbohydrates in favor of the roots. Undercutting has long been used to control the height of conifer seedlings.

For both red oak and walnut, undercut seedlings had greater numbers of total first-order permanent lateral roots than their uncut counterparts did (tables 1 and 2). The increased number of roots resulted from the addition of 2 to 6 wound roots and from the increased diameter of lateral roots already present above the wound. White oak showed similar results.

The number of wound roots produced is related to the timing of undercutting and to ambient conditions at the time of undercutting, such as temperature and moisture. Recent studies have focused on identifying these effects, and their initial results indicate that wound roots, as well as original laterals, persist and grow in the field (unpublished data).

The Iowa data are not presented here because of a practical problem with undercutting. Iowa seedlings were lifted above the depth of undercutting at harvest so that no new roots were recovered and the response could not be measured. If undercutting is intended to increase first-order roots on seedlings, the cut must be made well above the eventual lifting depth.

As bed density increased, fewer permanent first-order lateral roots were produced in both undercut and uncut treatments at all nurseries. At the Illinois nursery, density did not affect the number of

Table 2—*Responses of walnut seedlings to bed density and undercutting*

Density/ undercutting	Height (in)	Diameter (in)	No. of permanent roots > 1 mm		
			1st-order	Wound	Total
Illinois					
$3/ft^2$					
Yes	22.9	0.40	14.4	4.0	18.4
No	35.0	0.46	10.7	—	10.7
$6/ft^2$					
Yes	23.9	0.36	10.6	3.5	14.1
No	30.9	0.40	7.5	—	7.5
$9/ft^2$					
Yes	23.3	0.36	8.6	3.2	11.8
No	30.3	0.39	6.6	—	6.6
	D,U,DU	D,U	D,U	D	
Missouri					
$3/ft^2$					
Yes	14.6	0.30	11.7	4.6	16.3
No	17.0	0.32	13.7	—	13.7
$6/ft^2$					
Yes	15.9	0.28	8.8	4.1	12.9
No	18.3	0.30	9.8	—	9.8
$9/ft^2$					
Yes	17.9	0.26	6.4	3.3	9.7
No	19.6	0.27	8.2	—	8.2
	D,U,DU	D,U	D,U,DU	D	

Wound roots are > 1 mm developing around the undercutting wound. Significant (α = 0.01) effects of density (D), undercutting (U), and density by undercutting interaction (DU) were noted for the indicated characteristics.

wound roots produced by the undercutting treatment. At all other states, however, the number of wound roots produced decreased as density increased. These data show the strong effect that density control plays on the development of seedling root systems. To produce adequate root systems, the three hardwoods studied here should be grown at densities of no greater than 6 seedlings per square foot.

Figures 2 and 3 show the cumulative distribution of red oak and walnut seedlings (%) by numbers of first-order lateral roots, for two representative states. White oak showed a response similar to the response of both red oak and walnut. In all cases the undercutting treatment produced—at a given density—more seedlings with greater numbers of total first-order lateral roots (first-order laterals plus wound roots) than the no cutting treatment did. The undercutting treatment on 3 seedlings per square foot density produced the largest number of seedlings with large numbers of roots. The effect of both density and undercutting on lateral root production is clearly shown in these figures. Although the graphs are not identical, they are quite similar in actual values and in curve shape. Reducing bed densities and undercutting red and white oak and black walnut seedlings in the Central States will produce more seedlings with increased potential for both survival and good early growth in field.

Height and diameter correlations with numbers of roots. Although walnut shows very little height change with varying root numbers (fig. 4A), red oak shows a rapid increase in height as the

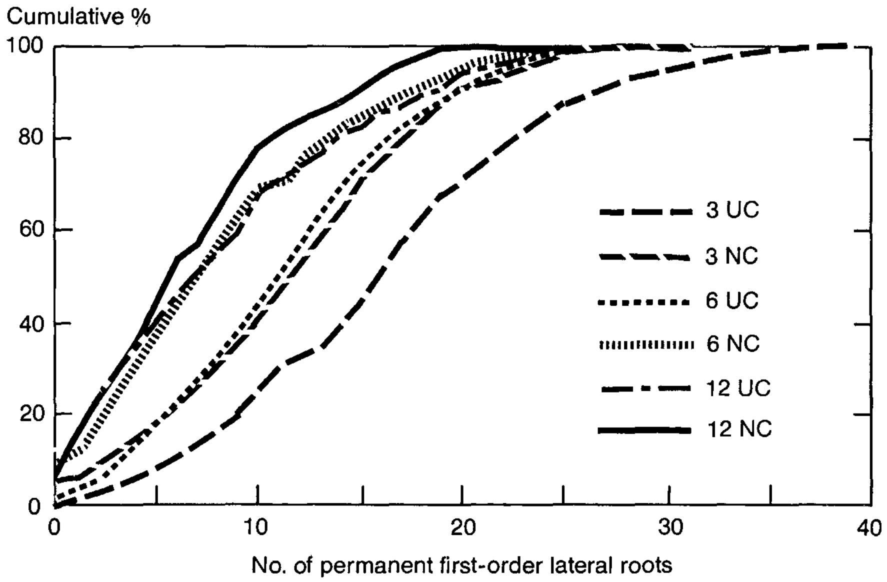

Figure 2—*Cumulative percentage of undercut (UC) and not cut (NC) 1+0 northern red oak seedlings lifted from Ohio nurseries in 1988, grown at densities of 3, 6, and 12 seedlings per square foot, with first-order laterals.*

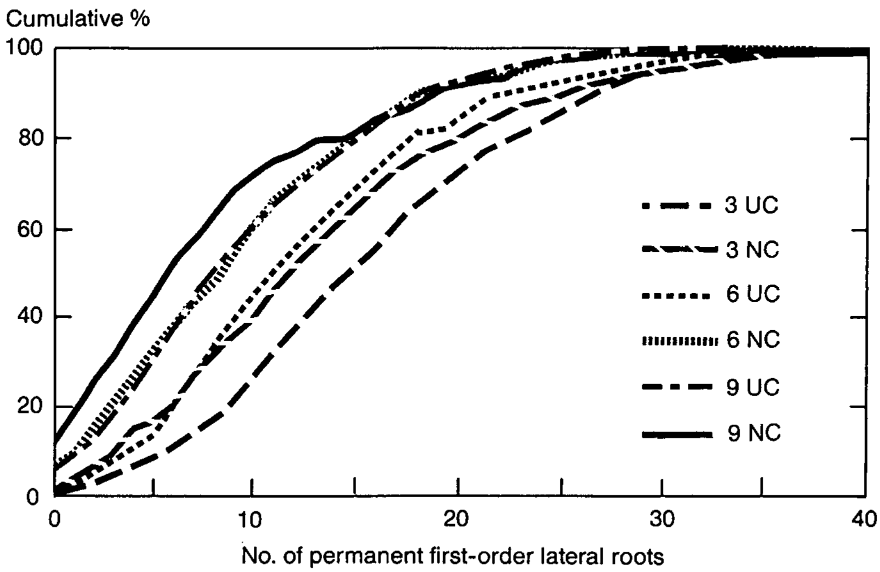

Figure 3—*Cumulative percentage of undercut (UC) and not cut (NC) 1+0 black walnut seedlings lifted from Missouri nurseries in 1988, grown at densities of 3, 6, and 9 seedlings per square foot, with first-order laterals.*

number of laterals increases from five to eight (fig. 5A). If root morphology is indeed important in the successful establishment of seedlings, grading walnut seedlings by height alone will not reflect their potential for success.

Seedling diameter also decreased as bed density increased and as undercutting proceeded. The differences in diameter between undercut seedlings and non-undercut seedlings were usually less than 0.2 inches. Figures 4B and 5B suggest that, especially among seedlings with lower numbers of roots, diameter may be a good predictor of root morphology. The ease of grading by stem diameter or by root number may differ, however.

Traditionally, seedlings have been graded by diameter, but it is doubtful whether most graders can estimate diameter well. It would probably be easier to inspect a seedling's root system to distinguish whether it has five to six or more permanent first-order roots than to determine whether it has a .25-inch stem diameter.

Responses to date and frequency of undercutting. In walnut seedlings in the Illinois nursery (fig. 6A-C) and in other states, the total number of first-order roots increased with later dates of undercutting and with more frequent undercutting. The increase resulted from both increased numbers of wound roots and increased diameters of laterals already present.

Illinois walnut seedlings undercut during the month of June and the first week in July showed greater height growth than uncut seedlings. Seedlings undercut on June 8 were probably too large for most field planting situations; those undercut on July 21 were smaller than the uncut seedlings but were still taller than 18 inches.

Diameters of seedlings showed few differences in response to undercutting. Seedlings undercut in late July had the smallest diameters, but the remaining seedlings exhibited few differences. Diameters in most cases were about 5/16 inch, a good size for walnuts.

Based on this information, it would seem best to undercut walnut once in late June or in early July. It is not necessary to use multiple undercuts unless there is a height growth problem. This recommendation is based on data from only 1 year and could change depending on the weather. There have been years when multiple undercutting was necessary to reduce dramatic height growth.

The number of permanent roots in Illinois red oak seedlings increased with later dates of undercutting, until late July (fig. 7A-C). However, even the late July undercutting produced more permanent lateral roots than were produced on the seedlings that had not been undercut.

Seedling height decreased with undercutting, especially for the two June dates. The late July date, which produced the fewest permanent lateral roots, produced the tallest undercut seedlings. This would suggest that undercutting redirects carbohydrate movement from shoot to root growth. The later the undercutting, the more the carbohydrate is directed to shoot growth before it is redirected.

Seedling diameter response was almost the opposite of height response. Diameters continually decreased with later undercutting dates, possibly because diameter growth is a late-season phenomenon. Early undercutting slowed shoot growth by redirecting carbohydrates to the roots, but did not

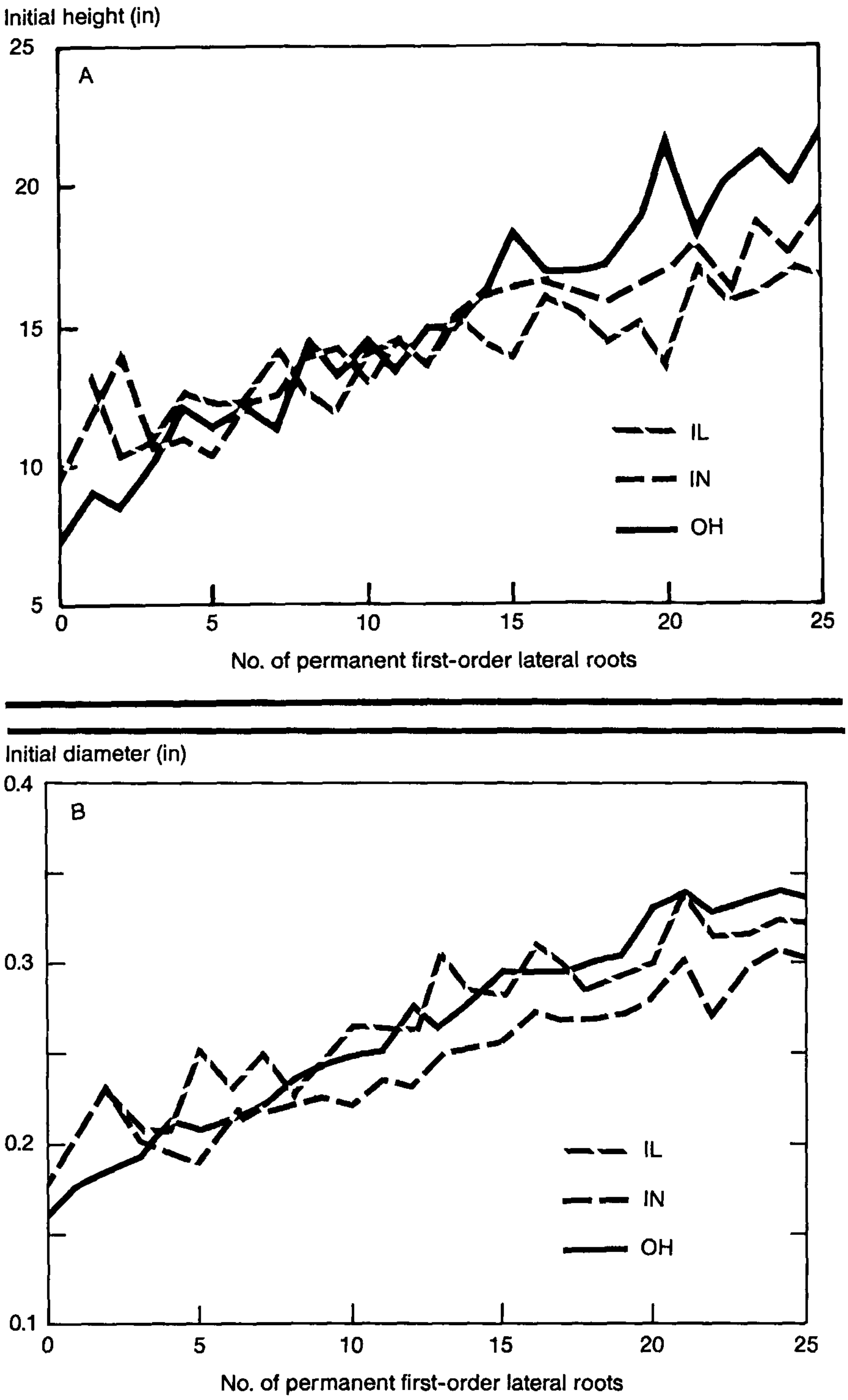

Figure 4—*Relation of initial height (A) and diameter* (**B**) *to total number of first-order laterals on 1+0 northern red oak seedlings grown in nurseries in Illinois (IL), Indiana (IN), and Ohio (OH) lifted in spring 1988. Values are means for the three densities.*

affect the diameter of these seedlings because wound roots had already been formed before major cambial growth activity began. With later undercutting, production of wound roots "robbed" the cambium of carbohydrates.

According to observations made during summer 1988, the ideal time to undercut red oak seedlings in the Central States is early to mid-July, after the second shoot flush has stopped. More specifically, seedlings should be undercut when the terminal bud has stopped expanding and the uppermost leaves have expanded to about three-quarters of their size. Another approach might be to undercut after the largest shoot flush has been completed.

In other words, undercutting should be done when the average shoot has almost reached the target height for saleable seedlings. From our observations it seems that only 3 to 4 weeks are needed for wound roots to be initiated and another 3 weeks are needed for those roots to suberize and become permanent.

The depth of undercutting is critical if the newly produced roots are to be lifted with the seedlings. Undercutting must be performed well above the lifting depth. In a nursery bed it is difficult to control undercutting depth precisely because of uneven bed heights and soil densities, but it should be possible to control depths to within 2 inches above or below the target

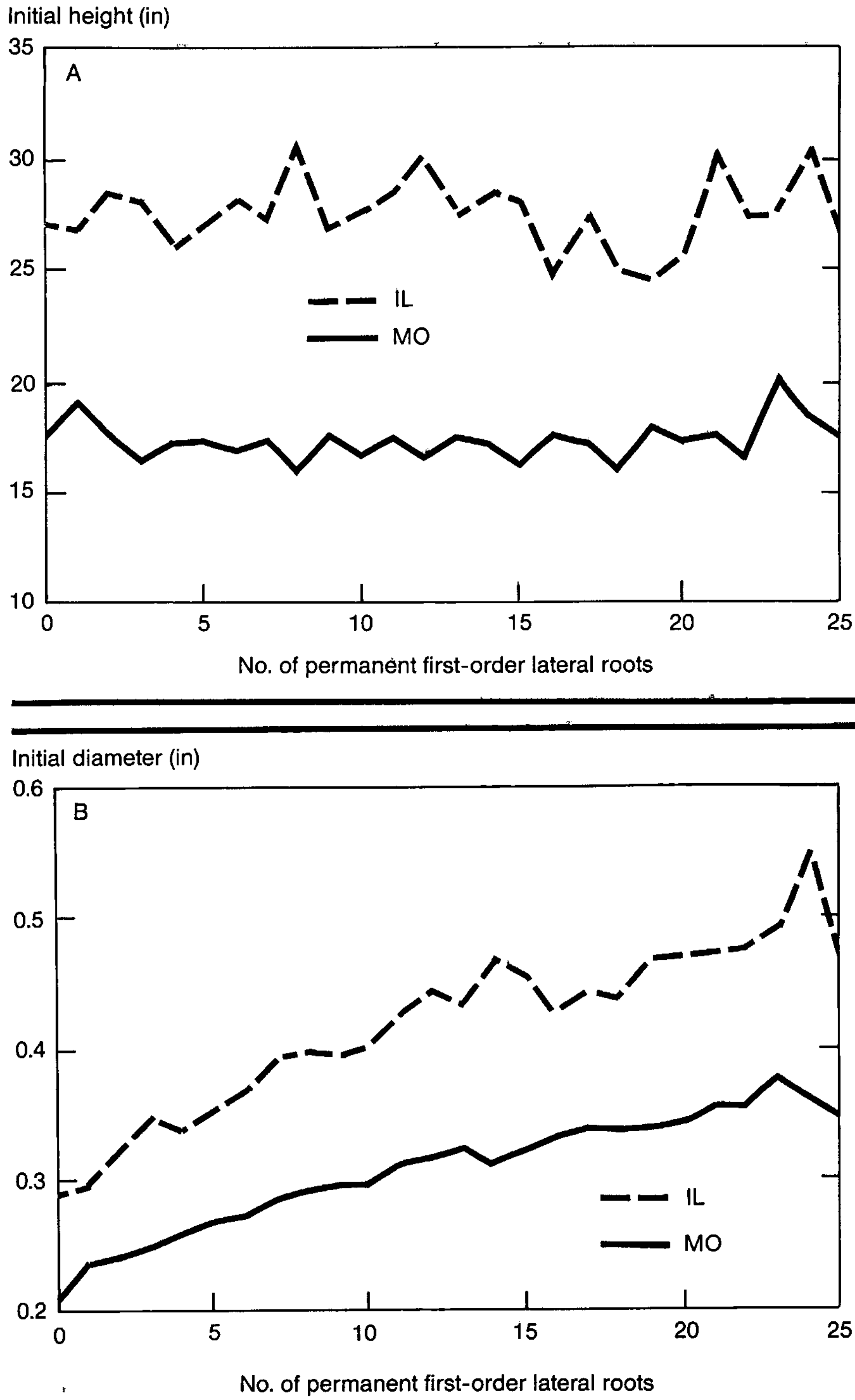

Figure 5—*Relation of initial height (***A***) and diameter (***B***) to total number of first-order laterals on 1+0 black walnut seedlings grown in nurseries in Illinois (IL) and Missouri (MO) at three densities and lifted in spring 1988.*

depth. Lifting depths are usually not deeper than 10 to 12 inches. Therefore, undercutting should be done at a depth of 6 to 8 inches. If lifting is done at shallower depths, then undercutting should also be shallower.

The ideal weather for undercutting is cool and moist, unlikely conditions for late June to mid-July. Thus, it is important for seedlings to be well irrigated no more than a day before undercutting. Seedlings should be undercut in the morning (6 to 10 am) or in the evening (after 7 pm). Seedlings should be irrigated again immediately after undercutting. It is unwise to undercut at temperatures exceeding 90 °F.

Casual observation suggests that seedlings that die as a result of undercutting are those having few lateral roots to begin with. In Iowa, in the summer of 1989, virtually all red oak seedlings that died after several beds were undercut pulled easily out of the ground because they had no roots. This suggests that under stress, undercutting seedlings could actually cull seedlings with poor root systems in the nursery bed. Research needs to be done to verify this phenomenon.

Mother-tree progeny tests. There was much variation among seed sources in terms of root numbers produced and associated height and diameters in red oak grown in Missouri (fig. 8) and walnut in Iowa (fig. 9). At this point, we believe more attention should be paid to the morphological characteristics of seedlings from specific mother trees. Future seed orchards should include only those trees producing a high number of seedlings with a minimum number of permanent first-order lateral roots.

Summary

In certain studies (Schultz and Thompson unpublished data) of the outplanting of numerous seedlings and in recent work by Kormanik and others *(1-3, 5)*, field survival and early growth of seedlings is strongly correlated with the number of permanent first-order lateral roots that a seedling develops in the nursery.

Information from our study suggests that a competitive northern red oak seedling must have a large root system with at least five permanent first-order lateral roots > 1 mm in diameter. White oak seedlings should have root systems similar to those recommended for red oak, and walnut seedlings should have eight or more large laterals. According to our study, after 2 years in the field, seedlings with those minimum numbers of roots had greater stem diameter and significantly larger leaf area (as inferred from the numbers of leaves) than seedlings with fewer roots.

The large number of bed-run seedlings produced that did not meet these minimum criteria suggests that root morphology should

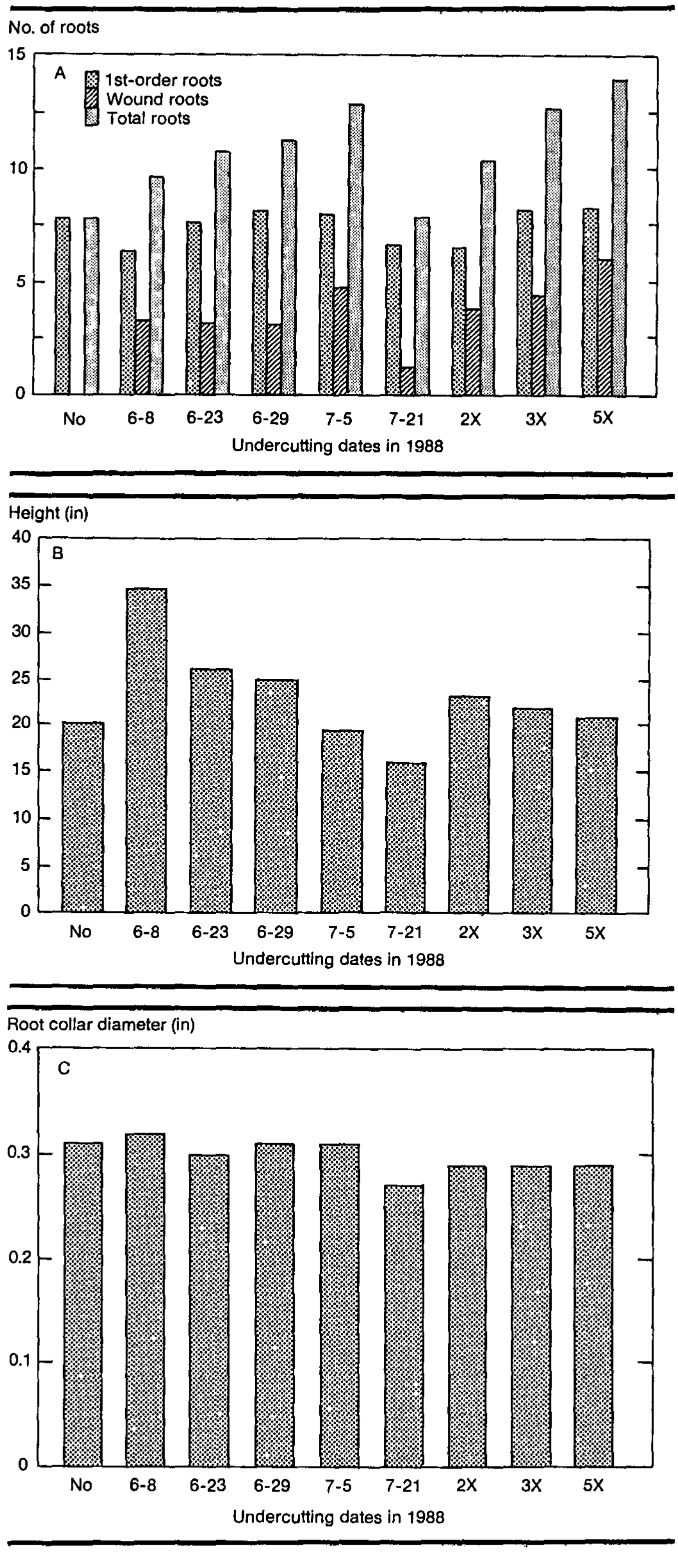

Figure 6—*Number of roots* **(A)**, *height* **(B)**, *and root collar diameter* **(C)** *of 1+0 black walnut seedlings grown in Illinois nurseries and undercut on different dates in 1988.*

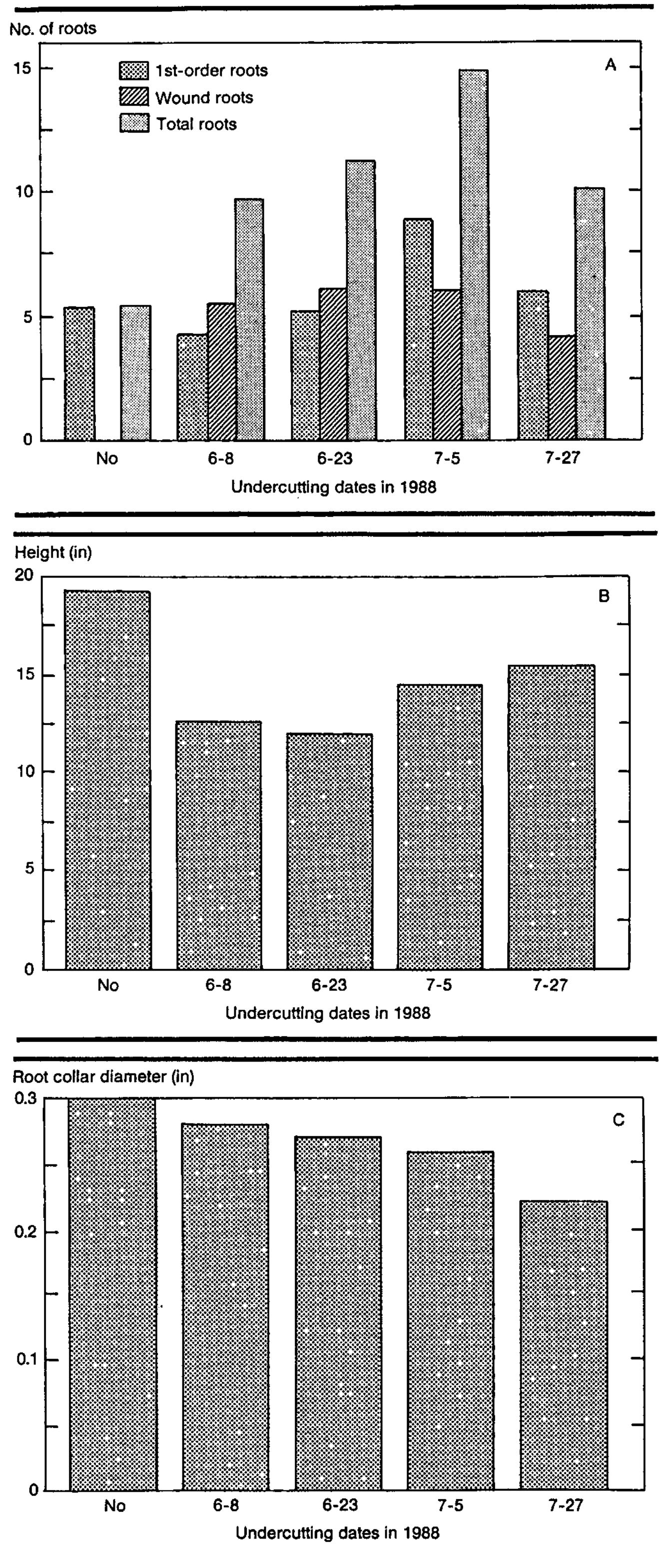

Figure 7—*Number of roots* (**A**), *height* (**B**), *and root collar diameter* (**C**) *of 1+0 northern red oak seedlings grown in Illinois nurseries and undercut on different dates in 1988.*

be a part of the grading scheme for bareroot seedlings. Nursery control of seedbed density and the use of timely undercutting can improve root morphology. However, there is a strong genetic component to root system expression that will require grading to eliminate root system culls *(3)*. Simply using height and/or diameter as grading criteria may not adequately identify potential for outplanting success. Recognition of the importance of root system morphology as a grading criterion will improve not only field survival but also early growth of seedlings.

According to the research work done in the cooperative, the ideal oak seedling is 14 to 16 inches tall, has a diameter of 1/4 inch, and has more than five to six permanent first-order lateral roots. The ideal walnut is 15 to 20 inches tall, has a diameter of 5/16 inch, and has 8 to 10 permanent first-order lateral roots.

Such large hardwood seedlings will require new approaches to planting. To improve hardwood seedling establishment and survival, larger equipment will be necessary to produce larger planting holes. The typical pine planting machine is inadequate for planting large hardwood seedlings, harming many larger root systems when they are forced through the machine. Larger planting machines are on the market and should be used.

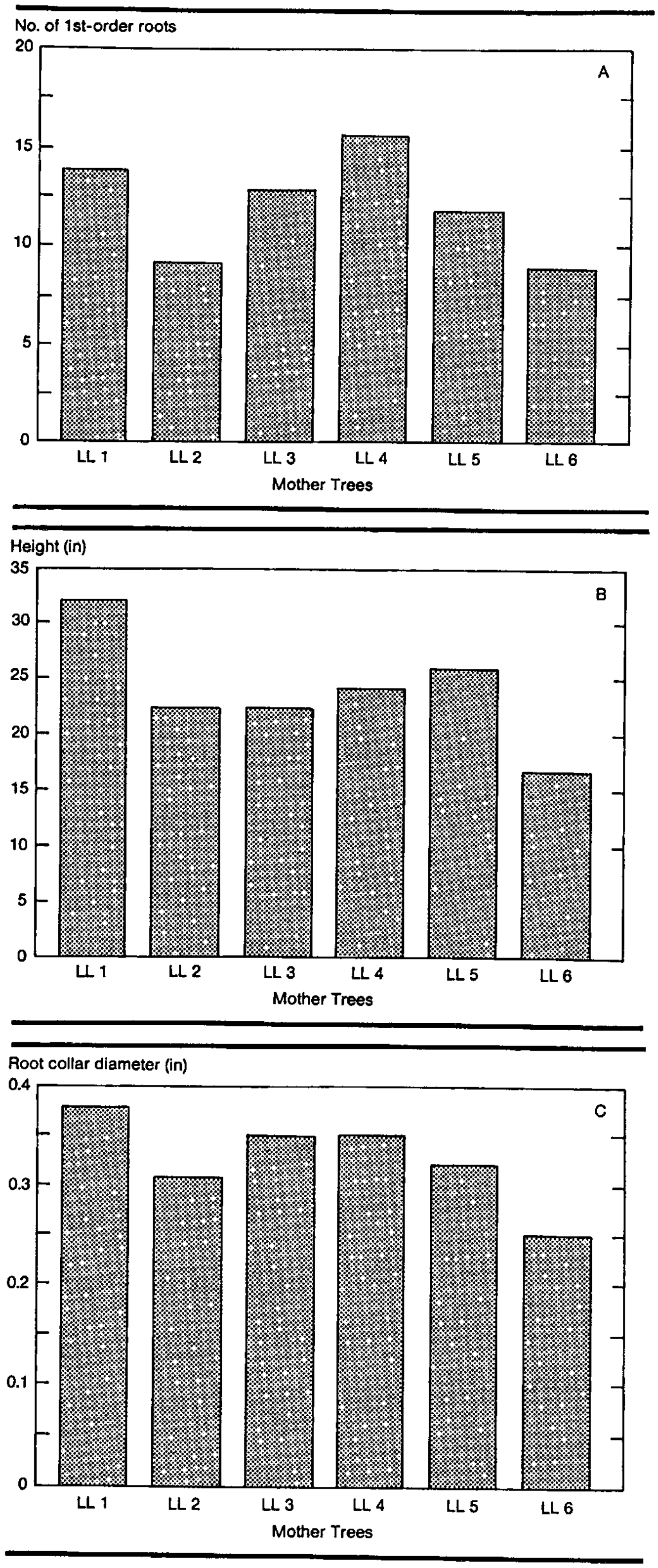

Figure 8—*Number of roots* **(A)**, *height* **(B)**, *and root collar diameter* **(C)** *of 1 + 0 northern red oak seedlings from different mother trees grown in Missouri nurseries in 1988.*

Hand planting with dibble bars is also impractical because the hole produced is not large enough. A shovel or large hodag may be necessary for hand planting. Portable two-person power augers are another option, for an 8-inch auger bit produces an adequate hole. Most of the seedlings planted for the cooperative studies were planted with such an auger. To date, there is no root morphological evidence that the auger hole constricts seedling roots if they are pruned to about 4 inches in length.

If establishing high-quality hardwood plantations is to be successful, large seedlings with well-developed permanent first-order root systems are necessary and must be planted with the proper equipment.

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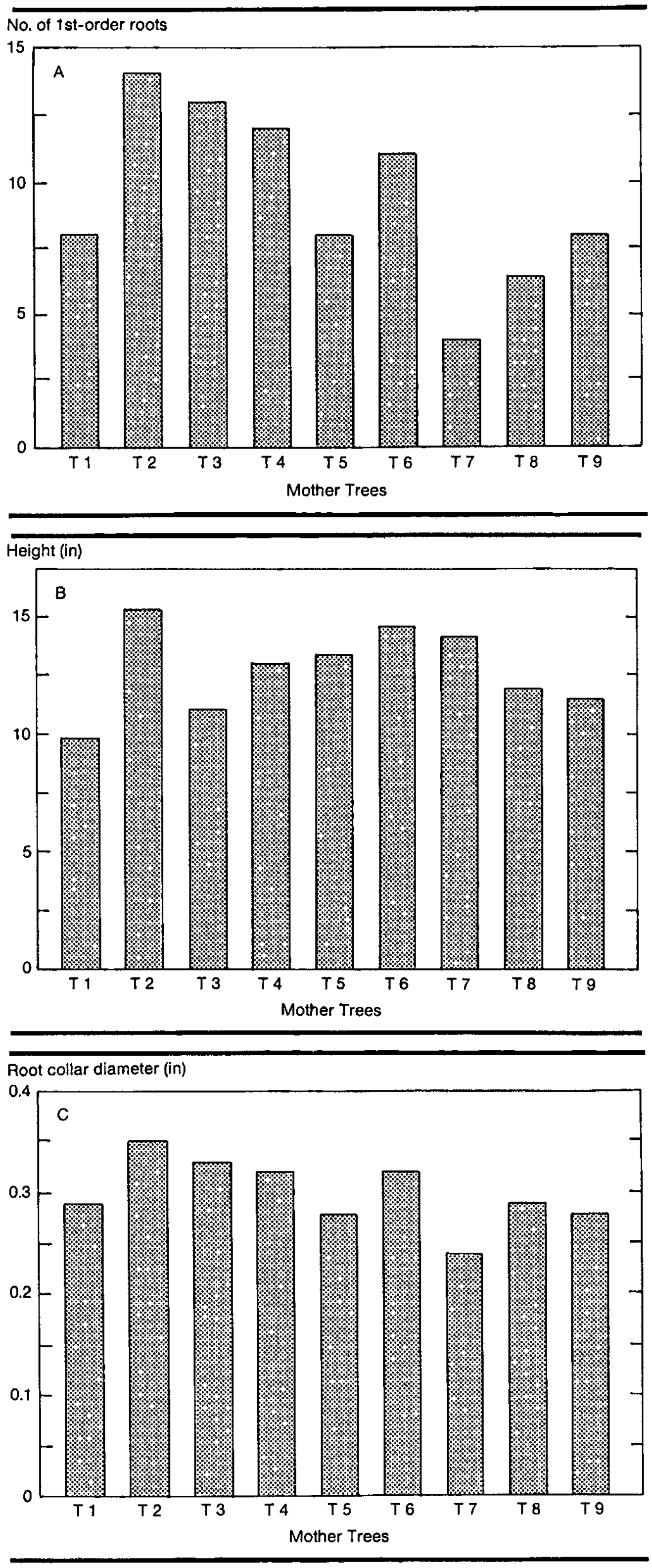

Figure 9—*Number of roots* **(A)**, *height* **(B)**, *and root collar diameter* **(C)** *of 1+0 black walnut oak seedlings from different mother trees grown in Iowa nurseries in 1988.*

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